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# Combining energy efficiency measure approaches and occupancy patterns in building modelling in the UK residential context

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ABSTRACT

The UK faces a significant retrofit challenge, especially with its housing stock of old, hard-to-treat solid walled dwellings. In this work, we investigate the delivery of heated thermal comfort with a lower energy demand through four types of energy efficiency interventions: passive system, conversion device, method of service control, and level of service demanded. These are compared for three distinct household occupancy patterns, corresponding to a working family, a working couple and a daytime-present couple. Energy efficiency measures are considered singly and in combination, to study whether multiple lower cost measures can achieve comparable savings to higher cost individual measures. Scenarios are simulated using engineering building modelling software TRNSYS with data taken from literature. Upgraded insulation of wall and roof resulted in highest savings in all occupancy scenarios, but comparable savings were calculated for reduced internal temperature and partial spatial heating in scenarios in which the house is not at maximum capacity. Zonal heating control is expected to achieve greatest savings for the working couple who had a flexible occupancy pattern. The results from this modelling work show the extent to which energy consumption depends on the appropriate matching between energy efficiency measures and occupant type.


## 1. Introduction

Domestic energy accounted for 29% of UK total energy use in 2013 [1] with space heating contributing 60% of this [2]. The UK has committed to reduce 80% of its greenhouse gases emissions by 2050 compared to 1990 levels (UK [3]). Even greater emission cuts are required in the building sector due to limited emission reduction potential in other areas, such as transport and industry [4]. Pressures to improve the energy efficiency of homes also come from trying to address high levels of fuel poverty and concerns over energy security. It is estimated that a majority of the buildings that will be in place in 2050 have already been built [5–7]. The culmination of these factors highlights the presence of a significant retrofit challenge. However, there is even evidence that figures for energy use in similar buildings vary greatly [8–10] and therefore a given energy use does not only depend on the standard of the fabric the house.

The aim of this paper is to demonstrate the variation of energy savings achieved by implementing different Energy Efficiency Measures (EEMs) for varied household occupancy patterns. In order to achieve this, a range of seven EEMs are chosen based on different approaches to delivering the energy service of heated thermal comfort. The savings achieved by the EEMs are compared for three different occupancy patterns which are derived based on common household scenarios in the UK, backed up by literature.

In order to calculate energy demand values before and after EEM interventions, a model of a typical UK 'hard-to-treat' house is developed using TRNSYS, a commercially available and well used building energy model. The modelling of the EEMs is based on literature data from academia and industry in order to attain the most likely values for model parameters before and after an intervention is adopted.

This paper begins with a literature review of related academic work in Section 2. The methodology is presented in Section 3 which includes an outline of the modelling process (Section 3.1), description of the EEMs which are selected according to how they deliver the energy service of heated thermal comfort (Section 3.2), and

*Abbreviations:* EEM, energy efficiency measure; TRV, thermostatic radiator valve; HDD, heating degree day.

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details of the occupancy patterns under consideration (Section 3.3). The results of the modelling work are revealed in Section 4, including a comparison of the results with similar studies, both empirical and modelled. Section 5 is the discussion, covering how the results relate to future and past policy priorities and additional considerations required when making recommendations for retrofit work. The paper concludes in Section 6 by recapping on what the paper has achieved and includes further steps which can be taken to gain additional insight into how EEMs can best be selected for different houses and occupants.

## 2. Literature review

### 2.1. Representing occupancy in building modelling

In recognition of the effect that occupancy behaviour has on real world energy use, the inclusion of more realistic occupancy profiles has been a focus of building modelling literature in recent years. As an approach to including realistic occupancy patterns, statistical pattern generators have been developed which take data from time use surveys (TUS) and create a tool for simulating random daily occupancy for model input [11–15]. Alternatively, occupancy archetypes have been defined to include in building modelling [16–19]. These allow for the variation between different types of occupants to be identified. Other studies have measured occupancy usage and behaviour directly and inputted these into building models to compare the modelled and measured data [20–22].

### 2.2. Retrofit decision models

The use of building energy modelling software to compare approaches to building retrofit is of current interest both within literature and policy programmes. In various policy programmes such as Energy Performance Certificates and the UK's Green Deal, the Standard Assessment Procedure (SAP) is used to predict savings from different energy efficiency measures and recommendations for retrofit are given. Within literature, models have been used to compare different approaches to improving the thermal resistance of the building envelope [17,23] and different heating strategies [18]. Rysanek and Choudhary [71] compared energy demand savings modelled for a range of single and combined improvements to energy supply systems and demand side measures in non-domestic buildings, with the inclusion of a stochastic model of occupancy behaviour, (including set-point temperatures, equipment use and lighting) and economic pay-back time. Recommendations for retrofit options could therefore be made based on real-world aspects of building use and decision making. De Meester et al. [17] investigated heating energy savings from increased insulation and three factors of human behaviour and occupation mode (family size and mode of occupation, thermostat setting and management of heating area). They found that equivalent savings could be attained by increasing insulation levels or by changing behavioural factors, but that the impact of behaviour on energy usage became smaller and less pronounced as the amount of insulation increased.

## 3. Methods and materials

### 3.1. Modelling process

In order to simulate energy demand savings for EEMs within this project, we are modelling a typical UK house using TRNSYS, a dynamic simulation software, which performs energy balance calculations using transient thermodynamic equations. By defining the building geometry, thermal envelope characteristics and occupancy details, the state of our building can be evaluated over

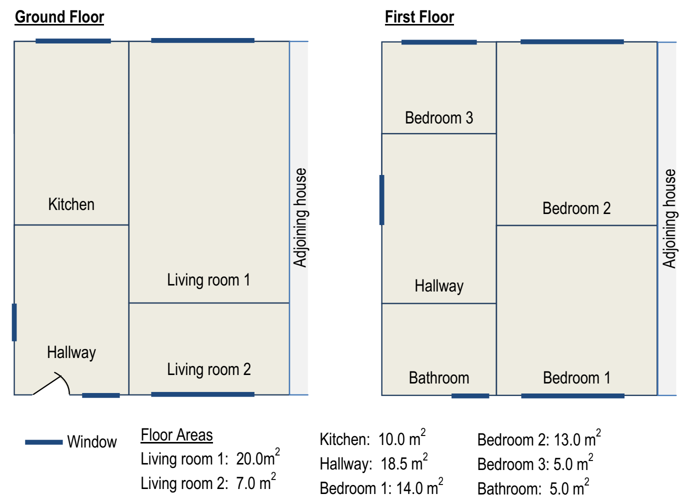


**Fig. 1.** Plan of modelled house.

15 min time steps. Table 1 lists and justifies modelling variables. The geometry of the house is shown in Fig. 1.

### 3.2. Energy efficiency measures

#### 3.2.1. Energy services approach to retrofit

EEMs are installed with the aim of delivering the service of a warm occupied space with lower energy input. The delivery of energy services has been discussed in literature as the step between energy supply and satisfaction of welfare [24]. The supply side of the energy system (comprising the conversion of primary energy to final delivered energy) has received the greatest attention in energy policy and therefore this paper focusses on the energy demand side of the chain. A framework has been developed using this theory of energy service delivery so as to identify four different approached of EEMs. The first two are derived from Cullen and Allwood [25] who describe the delivery of energy services from final energy as comprising an active conversion device and a passive system. The conversion device is the technical component which can convert an energy carrier into a useful form of energy (such as chemical energy within gas being converted into heat energy in a boiler). The passive system is 'the final technical component in the energy chain' within which the useful form of energy delivers an energy service (such as the room, with or without insulated walls, in which heat energy delivers thermal comfort). Technical efficiency improvements in the conversion device or the passive system can enable the same service to be delivered with lower energy input. The third option is a lower level of service demand, both in terms of internal temperature and amount of space heated. The level of energy service required to fulfil human welfare depends on lifestyle and is linked to cultural norms and habits [24,26] and therefore adapting to a lower level of service could be achieved both by adaptive methods or changes in societal expectations. Finally, inefficiencies in the way in which the energy service is delivered can be removed by better control and this is covered by the fourth approach, service control.

Data used in the modelling work has as far as possible been based on the most realistic values through a review of literature from academia and industry. The process for finding this data and the values identified are given in the following section. The values for initial and improved levels of each EEM are presented in Table 2.

#### 3.2.2. Conversion device: Boiler

Central heating is now the most common means of domestic heating in the UK, present in around 90% of households [27]. Typically, a boiler burns natural gas (mainly methane) to produce

**Table 1**
Description of modelling variables with justifications for chosen values.

| Modelling aspect | Value | Justification |
|---|---|---|
| House type | Semi-detached (aka twin/duplex) house | Accounts for around a quarter of houses [67] |
| House construction | Solid wall construction | Represents around a quarter of UK homes |
| Floor area | 92.5 $m^2$ | Typical three bedroom semi-detached house |
| Glazed wall area | Approximately 20% of the internal floor area of each room (10% for bathroom) | In line with current planning guidance [68] |
| Weather data (external temperature, humidity and solar radiation) | Meteonorm file for 'London, UK' | Representative of a typical meteorological year for the UK |
| Heating season | 1st October–30th April | Typical for the UK and suitable for the weather file used |
| Boundary temperature (for adjoined house | Identical | Represents the adjoining house being at the same temperature therefore there is no heat transfer |
| Ground temperature | 10 °C | A simplified ground floor heat loss model is adopted whereby heat transfer through the ground is driven by a ground temperature equal to the average annual air temperature [29] |
| Infiltration rate | Constant value of 0.75 air changes per hour (ach) | Representative of typical leaky house |
| Ventilation rate | – | Infiltration rate is above the recommended minimum value of 0.5 ach [69,70], and therefore further sources of ventilation are not included |
| Internal heat gains | – | As a simplification, no internal heat gains have been added into the model; these could be included to simulate aspects of occupancy beyond occupancy pattern such as cooking practices and appliance use. Although heat gains will affect heat demand calculations, by treating all model scenarios the same, the effect of this omission is not expected to affect the comparisons of variations in energy consumption and energy savings from EEMs and occupancy patterns |

heat which increases the temperature of hot water within the system (typically close to 65 °C). The hot water is pumped around the house, through room radiators in which the heat in the hot water is transferred to the air in the room, predominantly through the process of convection. The water which returns to the boiler is at a lower temperature (typically around 45 °C) and is heated up again as it passes through the boiler. For the purpose of modelling, it is assumed that the heat delivered to the house through the radiators is the model's calculated heat demand, and that this is directly replaced in the central heating fluid from the burning of gas.

Within the building model, the boiler is represented by a TRNSYS "equation component" which multiplies the total heat demand in each zone by the efficiency of the boiler and thus calculates the chemical energy in the gas. Boiler technology has improved since central heating was first installed in homes and new condensing boilers are capable of passing over 90% of the chemical energy in the gas to useful heat energy in the water under lab conditions. In reality, the efficiency of boilers used in homes do not achieve these standards, and an average in-use efficiency of a domestic A-rated condensing boiler was found by Orr and Summerfield [28] to be 85.6%. A typical efficiency of an old non-condensing boiler is 70%.

### 3.2.3. *Passive system: Thermal insulation*

The addition of insulation to a building envelope can significantly reduce the thermal transmittance, therefore retaining heat within a room of a house. The majority of new buildings have insulation in place, however many older buildings in the UK were not built with insulation, and therefore must have it retrofitted to improve thermal resistance.

Details of building construction are interpreted in a building energy model as thermal mass and thermal resistance. The thermal resistance of a building element is recorded (in the UK) in terms of

**Table 2**
Description of energy efficiency measures for modelling work.

| Energy efficiency measure type | | Energy efficiency measure | Description | Before | After |
|---|---|---|---|---|---|
| *A* | *Conversion device* | Boiler upgrade | Energy efficiency of heating system improved | 70% | 86% |
| *B* | Passive system | Solid wall Insulation | Thermal transmittance (*U*-value) of solid walls/Roof improved | 1.40 W/($m^2$ K) | 0.44 W/($m^2$ K) |
| *C* | | Roof Insulation | | 1.00 W/($m^2$ K) | 0.16 W/($m^2$ K) |
| *D* | Service control | Use of Thermostatic radiator valves (TRVs) | Set-point temperature in rooms varied according to temperatures typically desired | All rooms heated to 21 °C | Occupied temperature: living room, bathroom 21 °C; kitchen, hallway 19 °C, bedroom 17 °C |
| *E* | | Zonal heating controls | Alternative option for controlling temperature set point | Programmable thermostat controlling whole house | Individual programmed thermostats with control from outside the house |
| *F* | Service level | Reducing internal temperature | Internal temperature set point decreased throughout house | 21 °C | 1 °C reduction: 20 °C<br>2 °C reduction: 19 °C<br>(see Table 4) |
| *G* | | Partial heating of house | Unoccupied rooms to be unheated | All rooms heated | Secondary living space and bedrooms unheated in working couple and daytime present couple scenarios |

the thermal transmittance ($U$-value, W/(m$^2$ K)) and is the reciprocal of total thermal resistance. The $U$-value of a building element such as a wall can be calculated as the sum of the thermal resistance of each layer of the wall, plus edge effects. For a solid walled property (external walls made of a single layer of brick) insulation can be fixed internally or externally; in this model, internal insulation is considered.

The typical calculated $U$-value used for an un-insulated solid wall is 2.1 W/(m$^2$ K) [29,30]. However, published research on a number of empirical trials has shown this value to commonly be lower (higher thermal resistance) with measured values between 0.5 and 2.0 W/(m$^2$ K) [31–34]. For the purpose of modelling in this project, an un-insulated solid wall $U$-value of 1.40 W/(m$^2$ K) will be used. For the $U$-value of an insulated wall, building regulation standards for insulation specify that solid, as well as cavity walls, should be a maximum of 0.3 W/(m$^2$ K). However, this standard is difficult to achieve and a field study of solid wall insulation by the UK's Energy Saving Trust (EST) found an average $U$-value for solid walls with insulation of 0.44 W/(m$^2$ K) [31]. Therefore, a post-insulation $U$-value of 0.44 W/(m$^2$ K) is used in the modelling.

For the roof, national studies estimate that less than 1% of houses have no roof insulation at all [35] and therefore a base level representing a thickness of 0.03 m of mineral wool insulation is used, giving an initial $U$-value of 1.00 W/(m$^2$ K). Insulation is assigned to the horizontal base of the unheated roof space, between the joists, as opposed to on the pitched sides of the roof under the tiles. Improved insulation is implemented as 0.25 m thickness of mineral wool insulation, which is in accordance with building standards and has a $U$-value of 0.16 W/(m$^2$ K); this value is used in our modelling due to a general consensus in the literature and since insulating between rafters in the roof space is more straightforward than other types of insulation. All building envelope construction elements are described in Table 3.

#### 3.2.4. Service level: Internal temperature and heated floor area

Behaviour change approaches to energy reduction have been popular since the 1970s and continue to be a key approach by policy makers and community groups alike. Palmer et al. [36] made estimates for energy savings achieved by households adopting everyday 'behaviours' using their Cambridge Housing Model [37]. They found that reducing the thermostat temperature and turning off heating in unused rooms were amongst the 'behaviours' with the highest predicted energy savings. These two options both represent a change in the service level; demanded temperature and heated space.

Indoors comfortable temperature with cold outdoors is subjective and ambitions to quantify thermal comfort and indoor air temperatures have been studied both in terms of heat-balance methods [38–40] and the adaptive approach [41,42]. For representative temperature, typical measured temperatures have been investigated in literature. Published studies of measured internal temperature have shown winter average temperatures in the range 18 °C to 20 °C in the living room and 15 °C to 19 °C in the bedroom [43–48]. However, average temperature measurements include both heated and un-heated times of day, and do not represent temperature demand. Shipworth et al. [49] estimated a mean thermostat setting of 21.1 °C (SD = 2.5 °C) from temperature loggers in 427 study homes across the UK (a temperature which was significantly higher than the thermostat settings reported by the residents, which had a mean of 19.0 °C). Recommended minimum dwelling temperature in England is 18 °C in winter, exposing minimal risk to the health of a sedentary person, wearing suitable clothing [50].

For the purpose of modelling, initial temperature set-point of 21 °C is assumed, with the inclusion of heating controls allowing slight variation between rooms, as shown in Table 4. Temperature drops can commonly be endured through additional adaptive behaviour such as increasing clothing, with the addition of a thick sweater (0.3clo of insulation) reducing the required air temperature by around 1 °C [45] or estimated across a range from 0.5 to 2 °C [36]. Temperature reductions of 1 and 2 °C are investigated as EEMs.

Partial heating of a house has become less prevalent in the UK with the wide uptake of central heating, now in 90% of residences [27]. The existence of partial house heating may remain unavoidable due to the pressures of fuel poverty, but in other cases it is chosen due to changes in occupancy of a house and rooms becoming surplus. As household characteristics change, for instance with children growing up and moving out, parts of the house cease to be occupied for large periods of time and could be left unheated for these long periods. Alternatively, if occupancy is lower than maximum at times during the day, such as for one person working from home, parts of the house can be unheated at certain times of the day only, especially with appropriate heating control. The EEM of partial heating has been represented in the model as no heating in unoccupied room (Living room 2 and Bedrooms 2&3 in occupancy profiles of fewer than four people), or following the introduction of thermostatic radiator valves (TRV) and zonal heating control (see Section 3.2.5), as a low heating set point in those rooms which are unoccupied.

#### 3.2.5. Service control: Heating controls

Accurate control of heating can avoid considerable energy wastage; if a room is heated whilst unoccupied, no service is being delivered and therefore energy is consumed for no delivered benefit.

The most common central heating controls are a room thermostat, TRVs, and a programmable heating control which sets on-off times for heating. The innovation in wireless control and the availability of more powerful batteries have led manufacturers to develop advanced heating controls which allow room-by-room zonal control of space heating [51]. These controls allow the set point temperature of rooms to be adjusted on different time-schedules based on a household's occupancy patterns. These also have the capability to be controlled remotely, for instance from a computer or smart phone, giving a household flexibility to change the heating times daily around their personal agenda.

Based on a survey of the existing UK landscape of heating controls [27], the initial case for heating controls in the model is a heating timer and a room thermostat. The heating can thus be set to turn on half an hour before an occupancy period and off at the end of it, but set-point temperature is the same throughout the whole house. The same pattern is used throughout the week as studies have shown little difference between the temperature profiles of homes on weekdays and weekends [44,52]. A first improvement for service control is the use of TRVs in order to provide an appropriate temperature in each room. The TRV allows temperature setting on a sliding scale, typically 0–5, which controls the water flow through the radiator. Calibration of TRV setting to temperature varies by model, but typically allows temperature control between 12 °C and 23 °C. A second level of improvement is the introduction of advanced 'zonal' heating controls with the ability to set different temperatures profile for each room, and to control the heating remotely. Heating controls are represented in the building modelling as heating set-point temperature schedules which vary according to occupancy profile and control approach.

#### 3.2.6. Combinations of measures

In reality, households are not restricted to making single changes. One example of this is in insulation of the building shell; it is unlikely that wall insulation would be completed in isolation

**Table 3**
Wall, roof and window construction used in model.

| Building element | Thermal resistance level | Material | Thickness (m) | *U*-value (W/(m² K)) |
|---|---|---|---|---|
| Wall (Solid wall construction) | Pre-insulation (empirical *U*-value) | Brick | 0.360 | 1.40 |
| | | Plaster | 0.045 | |
| | Typical insulated (internal wall insulation) | Brick | 0.360 | 0.44 |
| | | Insulation (mineral wool) | 0.065 | |
| | | Plasterboard | 0.020 | |
| Internal walls | Typical construction | Plaster | 0.013 | 1.52 |
| | | Brick | 0.215 | |
| | | Plaster | 0.013 | |
| Boundary walls | Typical construction | Plasterboard | 0.012 | 1.40 |
| | | Brick | 0.220 | |
| | | Plasterboard | 0.012 | |
| Roof (horizontal base of roof space | Pre-insulation (empirical *U*-value) | Insulation (Mineral wool) | 0.032 | 1.00 |
| | | Plasterboard | 0.012 | |
| | Typical insulated | Insulation (Mineral wool) | 0.250 | 0.16 |
| | | Plasterboard | 0.012 | |
| Roof tiles | Typical construction | Tiles | 0.02 | 5.26 |
| Windows | Double glazed | | 2.83 | |
| Ground Floor (solid) | Typical construction (solid concrete floor) | Plywood | 0.010 | 0.86 |
| | | Concrete | 0.100 | |

**Table 4**
Temperature set-points throughout house used in initial case and for one or two degree temperature reduction.

| Room or zone | Set point temperatures (°C) | | |
|---|---|---|---|
| | Initial | 1 °C reduction | 2 °C reduction |
| Nominal internal temperature | 21 | 20 | 19 |
| House thermostat[1] | 21 | 20 | 19 |
| Living room | 21 | 20 | 19 |
| Kitchen | 19 | 18 | 17 |
| Kitchen[2] | 19 | 18 | 17 |
| Bathroom | 21 | 20 | 19 |
| Hall | 19 | 18 | 17 |
| Night time | 17 | 16 | 15 |
| Low temperature set-point when heating off | 12 | 12 | 12 |
| Low temperature set-point when room unoccupied | 15 | 15 | 15 |
| Low temperature set-point when house unoccupied | 14 | 14 | 14 |

[1] In initial heating scenarios of programmable timer, all rooms are set at this value of house thermostat.
[2] This value is used for bedroom during waking hours in zonal heating scenarios, but drops to night time temperature during sleeping hours.

if the roof is not already well insulated, and therefore roof and wall insulation are a likely joint measure. If the availability of finance or threats of disruption are constraints to improved building energy efficiency, combinations of low or no cost measures could result in savings equivalent to more expensive and invasive energy efficiency work. Table 5 shows indicators of cost for the EEMs. Table 6 gives the full list of combined measures being considered alongside single measures.

### 3.3. Occupancy patterns

The occupancy patterns in this study have been derived from the information gained from literature, both measured temperature profiles [52,53] and identified common household scenarios

**Table 5**
Cost factors and indicators for energy efficiency measures.

| EEM | Costs | Cost indicator |
|---|---|---|
| Boiler replacement | New boiler, installation, possibly new pipework | High |
| Roof Insulation | Insulation, possible installation | Medium |
| Wall Insulation | Insulation, installation, possibly aesthetic repairs afterwards | Very high |
| Temperature reduction | Thermostat if not in place already | Low or no cost |
| Partial heating | TRV if not in place already | Low or no cost |
| Zonal heating control | Heating controls, possibly installation | Medium |

**Table 6**
Outline of combinations of measures investigated in the present work.

| Combination of measures | Justification |
|---|---|
| Roof and wall insulation | It is realistic to expect that wall insulation would be accompanied by roof insulation if this is not already in place and therefore it is appropriate to consider these combined as an EEM |
| Heating controls (TRV or zonal control) *plus* Partial heating | Partial heating can be achieved more easily with the introduction of more advanced heating controls. In these cases, partial heating is simulated by a set temperature of 15 °C |
| Heating controls (TRV or zonal control) *plus* 1 °C temperature reduction | Improved heating controls can allow for better controlling of the set-point temperature, and facilitate a temperature reduction |
| Heating controls (TRV or zonal control) *plus* Partial heating *plus* 1 °C temperature reduction | Partial control and temperature reduction are behavioural EEMs and therefore have no financial cost and can be implemented alongside other measures |

**Table 7**
Description of occupancy patterns used in modelling.

| Occupancy pattern | Description |
|---|---|
| Working family | House occupied by family (2 adults who work externally and 2 children). All occupants are absent 08.30–16.00. When the family is home, all areas of the house are usually occupied |
| Working Couple | House occupied by couple (2 adults who work externally during the day). All occupants are absent during the day, and sometimes in the evenings: four days per week 08.30–18.00, three days per week 08.30–21.00. When the couple is home, the house is partially occupied with one bedroom and one living room often not being used |
| Daytime-present Couple | House occupied by couple (2 adults, one or both of whom are usually home during the day). The house is usually only partially occupied, with one bedroom and one living space often not being used |

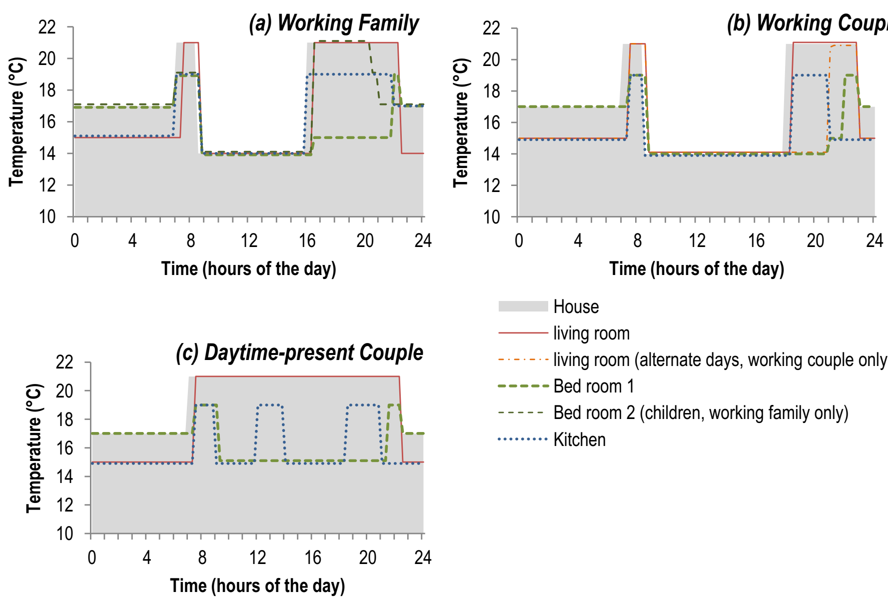


**Fig. 2.** Ideal temperature profiles in different rooms for each of the three occupancy patterns. Shaded area shows baseline heating control using programmable timer thermostat (some temperature profiles have been off-set for greater visual clarity).

[16–19,54]. Three different patterns have therefore been chosen to reflect a diversity of typical UK households, whilst not trying to represent all households. The first pattern is a working family whose members are absent during the day but with a regular pattern through the week and can be expected to represent 28% of the population, including couples and single parents with children [55]. The second pattern is that of a working couple who is absent from the house during the day and returns to the house at varying times through the week; this pattern may represent 28% of the population [55]. The final pattern is that of a couple of which one or both remain in the house throughout the majority of the day. Daytime occupancy has typically been attributed to a 'retired couple' but in reality there are a range of other reasons for people remaining at home during the day, such as working from home, being jobless or being house-bound due to disability. This third pattern is referred to as daytime-present couple and could represent 29% of the population when including households over 75 years old [56] and home workers [57]. These occupancy profiles are further described in Table 7 and resulting temperature profiles for some rooms are displayed in Fig. 2.

## 4. Results

### 4.1. Comparison of EEMs in reducing energy demand

Single and combinations of EEMs have been modelled for each occupancy pattern. The values of energy demand for heating over a 1 year period are compared in Fig. 3. Due to the external temperature profile chosen for a typical year in London, UK, heating is usually only required during the period October–April. Artificial cooling demand in summer is not modelled, as this is, to date, rare for UK homes. Table 8 shows a key to the implemented EEMs.

In all cases, the single measure with the greatest savings potential was the wall insulation (C) followed by the boiler upgrade (A), demonstrating the importance of high efficiency both for passive systems in retaining heat and conversion devices transforming final delivered energy input to useable heat energy. Service level measures showed potential for significant savings, both for temperature reduction (F) and partial heating (G). Improvements in roof insulation (B) and zonal heating controls (E) (in all but working family occupancy pattern) resulted in comparable savings. When considering combinations of measures, full passive system upgrade (insulation of wall and roof (BC)) gave highest savings over all, but were closely followed in two of the occupancy patterns by service level changes of 1 °C temperature reduction combined with partial heating and zonal heating control (FG, EFG). Combining lower cost measures of service level and service control (heating controls) led to savings at the same level as higher cost passive system upgrades.

### 4.2. Comparison of EEM savings across occupancy patterns

The savings in heating energy demand have been calculated compared to the initial scenario. These are shown in Fig. 4 and are ranked for each occupancy pattern in Table 9.

For some EEMs, the savings were similar for all three occupancy patterns. These include roof (B), wall (C) and combined insulation (BC), boiler upgrade (A) and temperature reductions (F). In other cases, the savings varied greatly between occupancy patterns. Partial heating (G) produced large savings of 17–18% in the houses with less than full occupancy (working couple and daytime-present

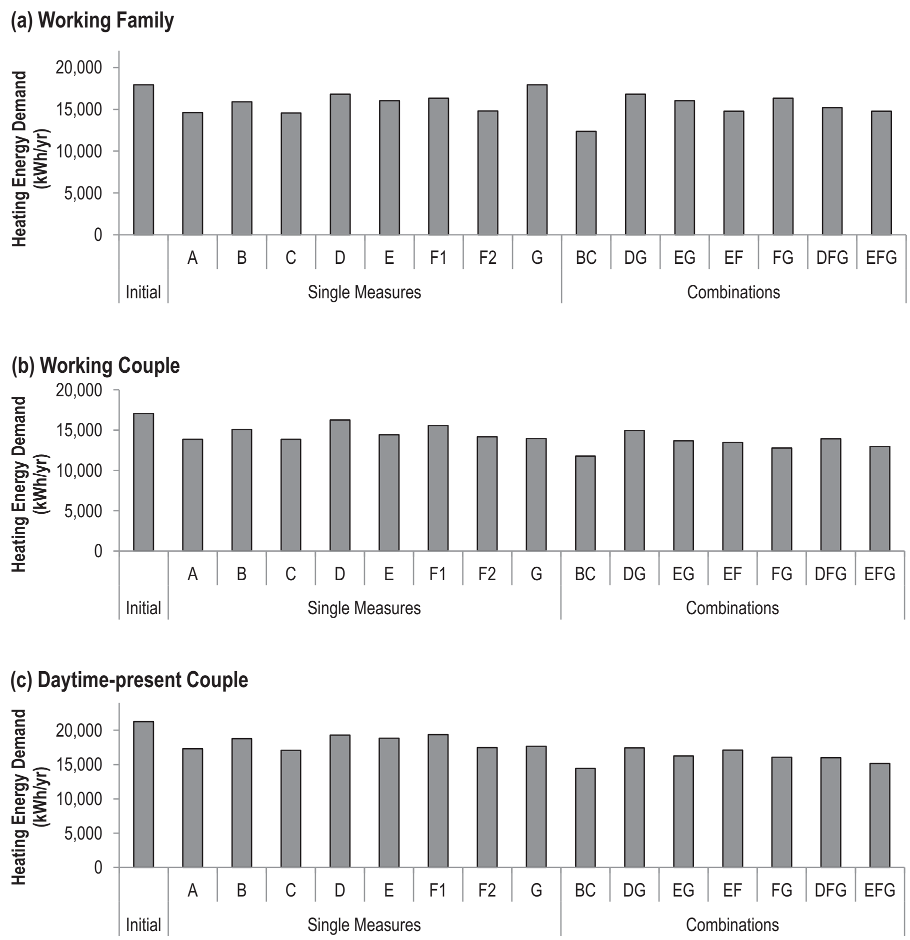


**Fig. 3.** Modelled energy demand for heating values for three occupancy patterns and a range of single and combinations of energy efficiency measures. EEMs are given in key in Table 8.

couple), whilst no savings were considered possible for the working family who would occupy the whole house. TRVs (D) enabled greater savings for cases with higher occupancy hours; 9% for the couple present in the daytime whilst only 5% for the working couple. Zonal heating controls (E), including remote control of the heating to coincide with variable daily pattern, resulted in greatest savings for the working couple. There were greater variations between savings for different occupancy patterns when considering combinations of measures. Energy saving potential was greatest for day-time present couple and working couple, with seven and five single or combinations of EEMs respectively which predicted savings above 20%.

**Table 8**
Key to EEMs (single and combinations) plotted in Figs. 3 and 4.

| Energy Efficiency Measures | Conversion Device | Passive System | | Service Control | | Service Level | |
|---|---|---|---|---|---|---|---|
| | A: Boiler upgrade | B: Roof insulation | C: Wall insulation | D: TRV | E: Zonal heating controls | F: Temperature reduction | G: Partial heating |
| **Single** | | | | | | | |
| *Initial* | | | | | | | |
| A | x | | | | | | |
| B | | x | | | | | |
| C | | | x | | | | |
| D | | | | x | | | |
| E | | | | | x | | |
| F1 | | | | | | 1 °C | |
| F2 | | | | | | 2 °C | |
| G | | | | | | | x |
| **Combinations** | | | | | | | |
| BC | | x | x | | | | |
| DG | | | | x | | | x |
| EG | | | | | x | | x |
| EF | | | | | x | 1 °C | |
| FG | | | | | | 1 °C | x |
| DFG | | | | x | | 1 °C | x |
| EFG | | | | | x | 1 °C | x |

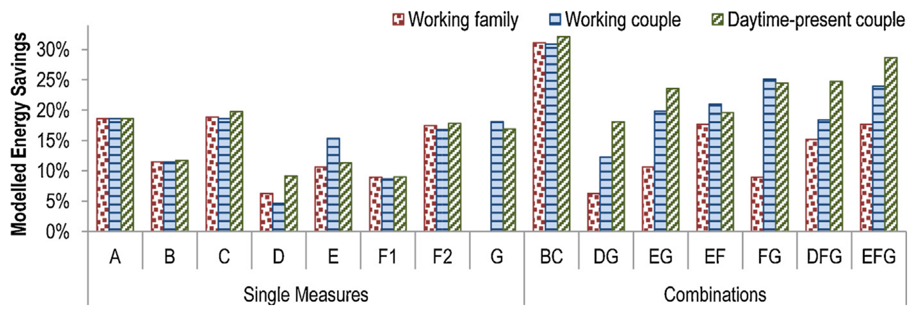


**Fig. 4.** Modelled energy savings for single and combinations of energy efficiency measures for three occupancy patterns. EEMs are defined in key in Table 8.

### 4.3. Comparison of results with expected values

A residential building is a complex system in which technical aspects such as structural engineering, thermodynamics and heat transfer interact with many human elements; not only how occupants use and live in their house, but also the competence with which the house was constructed and any upgrades are implemented. Consequently, even if the engineering calculations are complete, there will be limitations in how accurately the model can represent reality. Simplification made by the authors (for infiltration, ventilation, internal gains and detailed occupant interactions with the house) mean that the modelled results cannot be expected to perfectly represent real world energy use. However, by comparing the simulation values to similar figures from other sources, the results can be critically assessed.

For overall energy consumption, a statistical benchmark has been taken from the UK Government's Department of Energy and Climate Change (DECC) National Energy Efficiency Data-framework (NEED) [58]. The dataset provides measures of gas and electricity use from 3.5 million UK homes for 2012, classified by regional location, house type, number of bedrooms and energy supply. Gas usage figures for a three bedroom semi-detached house in South East England are considered as the best match to the building model in this paper (average total heating degree days (HDDs) across the South-East of England in the year 2012 were calculated as 2010 $^{\circ}$C days [66] showing a close match to HDDs in model weather file of 2013 $^{\circ}$C days). The year of construction is pre 1919 as for this period 86% of houses have a solid wall construction. The level of energy efficiency cannot be ascertained, but is expected to be more representative of the pre-EEM figures as initial values used in the model are based on typical current levels. National statistical data of domestic energy consumption by end use quotes space heating as accounting for 69% of total gas use [1,59] and therefore this factor will be applied to the statistical benchmark to convert figures to space heating energy only. This adjustment disregards occupancy pattern in making the conversion from total gas use to gas consumed for heating, due to a lack of more specific data. Although gas use for cooking and hot water can be assumed to be lower for a couple than a family, it is not clear how this would affect the proportion of total gas consumption used for heating.

In order to validate the individual EEMs, comparable data has been taken from literature. This comprises statistical average

**Table 9**
Energy demand savings calculated for single and combinations of EEMs for three occupancy patterns, ranked and grouped according to level of savings achieved. (Italics are used for single measures).

| Energy savings | Working family | % | Working couple | % | Daytime-present couple | % |
|---|---|---|---|---|---|---|
| *Initial Energy Demand* | 17,940 kW h/yr | | 17,050 kW h/yr | | 21,260 kW h/yr | |
| ***>25%*** | Roof **and** Wall insulation | 30 | Roof **and** wall insulation | 31 | Roof **and** wall insulation | 32 |
| | | | 1 $^{\circ}$C temp reduction **and** partial heating | 25 | 1 $^{\circ}$C temp reduction, partial **and** zonal control | 29 |
| | | | | | 1 $^{\circ}$C temp reduction **and** partial heating **with** TRV | 25 |
| ***20–25%*** | | | 1 $^{\circ}$C temp reduction, partial **and** zonal heating | 24 | 1 $^{\circ}$C temp reduction **and** partial heating | 24 |
| | | | 1 $^{\circ}$C temp reduction **and** zonal heating | 21 | Partial heating **with** zonal heating control | 24 |
| | | | Partial and zonal heating | 20 | *Wall insulation* | 20 |
| | | | | | 1 $^{\circ}$C temp reduction **and** zonal heating control | 20 |
| ***15–20%*** | *Wall insulation* | 19 | *Wall insulation* | 19 | *Boiler upgrade* | 19 |
| | *Boiler upgrade* | 19 | *Boiler upgrade* | 19 | Partial heating **with** TRV | 18 |
| | 1 $^{\circ}$C temp reduction and zonal control | 18 | 1 $^{\circ}$C temp reduction **and** partial heating **with** TRV | 18 | *Temperature reduced by 2 $^{\circ}$C* | 18 |
| | 1 $^{\circ}$C temp reduction, zonal control **and** partial heating | 18 | *Partial heating* | 18 | *Partial heating* | 17 |
| | *Temperature reduced by 2 $^{\circ}$C* | 17 | *Temperature reduced by 2 $^{\circ}$C* | 17 | | |
| | 1 $^{\circ}$C temp reduction **and** TRV | 15 | *Zonal heating controls* | 15 | | |
| ***10–15%*** | *Roof insulation* | 11 | Partial heating **with** TRV | 12 | *Roof insulation* | 12 |
| | *Zonal heating controls* | 11 | *Roof insulation* | 11 | Zonal heating controls | 11 |
| | Zonal heating control **and** partial heating | 11 | | | | |
| ***5–10%*** | *Temperature reduced by 1 $^{\circ}$C* | 9 | *Temperature reduced by 1 $^{\circ}$C* | 9 | *TRV* | 9 |
| | *TRV* | 6 | *TRV* | 5 | *Temperature reduced by 1 $^{\circ}$C* | 9 |
| | TRV **and** partial heating | 6 | | | | |
| ***<5%*** | *Partial heating* | 0 | | | | |

**Table 10**
Comparison between model data and data taken from literature for total energy demand and savings due to EEMs.

| | Comparison data | | | | | Model data | | |
|---|---|---|---|---|---|---|---|---|
| | Data type | Sample size | Median value | Upper quartile | Lower quartile | Working family | Working couple | Daytime-present couple |
| Annual heating demand/consumption (kW h/yr) | S[1] | 7000 | 11,300 | 14,600 | 8400 | 18,594 | 17,636 | 22,202 |
| Energy efficiency measures savings (%) | | | | | | | | |
| Roof insulation | S[2] | 20,470 | 2.8 | 18 | −13 | 11 | 11 | 12 |
| Solid wall insulation | S[2] | 830 | 14.2 | 31 | −3 | 19 | 19 | 20 |
| Boiler upgrade | | | | | | | | |
| -All house types | S[2] | 13,970 | 10.7 | 27.9 | −5.7 | 19 | 19 | 19 |
| -3 Bedroom semi-detached | | 3410 | 12.4 | 27.5 | −7.7 | | | |
| Zonal heating controls | E[3] | 1 | 14.1 | – | – | 11 | 15 | 11 |
| Thermostat temp reduced | | | | | | | | |
| -1 °C | M[4] | – | 9 | – | – | 9 | 9 | 9 |
| -2 °C | | | 13 | | | 17 | 17 | 18 |
| Partial heating of house | M[4] | – | 4 | – | – | 0 | 18 | 17 |

*S*: statistical average; *E*: empirical study; *M*: model estimates.
*Data source:* [1] [58]; [2] [62]; [3] [51]; [4] [36].

energy savings for insulation and boiler upgrades, an empirical study into energy savings achieved by zonal heating control and modelling work using the Cambridge Housing Model [37] into energy savings by common household ‘behaviours’. Model results, statistical benchmarks and representative values for EEM energy savings are presented in Table 10.

The model calculated value of annual heating demand is significantly higher than the statistical values for gas consumption. This discrepancy could be due to modelling approximations, such as neglect of internal heat gain or incorrect assumptions of the state of a typical home prior to energy efficiency improvements. A number of occupancy related inputs could have been included, such as appliance use, window opening habit and use of secondary heating, but it has been beyond the scope of the project to analyse their effects and instead only occupancy pattern was included in this study. The disagreement could also result from errors in the conversion between calculated heat demand and measured gas consumption, a step which is very sensitive to the assumed values for boiler efficiency and percentage of gas consumption due to space heating. In reality, heat demand is not always satisfied within a system, but a model assumes that it is; the model in this study uses the method of heat demand calculation typically used in engineering model calculations, but this does not represent the actual functioning of a central heating system.

When comparing the model predicted savings with values taken from literature, some EEMs show a good match and others significantly disagree. Zonal heating control and thermostat temperature reduction of 1 °C show a close match between modelled and comparison values. Solid wall insulation and 2 °C thermostat temperature reduction are in fair agreement. Savings values for roof insulation, boiler upgrade and partial heating of the house do not correspond. With regards to partial heating of the house, this discrepancy could be due to neglecting internal heat transfer between zones; flow of heat from a warmed room to a cool room would reduce the energy savings overall. However, the comparison value is also the result of modelling work (rather than empirical study) and therefore errors in assumptions by Palmer et al. [36] could also contribute to the discrepancy. The modelled values for roof insulation and boiler upgrade savings are far higher than the median value taken from DECC’s statistics, though they are significantly less than the value of the upper quartile. The broad range of values for measured savings following roof insulation can be due to different states of roof insulation prior to the intervention, or poorly installed insulation which falls short of required building standards. Another reason for the discrepancy between modelled and measured savings could be rebound effects whereby energy savings are compromised by households taking other benefits (such as comfort taking by raising the internal temperature) [60,61]. The rebound effect has not been considered in this study as the wide ranging implications cannot be easily predicted. Since the effect on energy savings could be seen after any EEM and could affect each occupancy pattern similarly, its inclusion would distract from the results which are presented.

## 5. Discussion

Four approaches to delivering the energy service of heated thermal comfort with less energy demand have been investigated; improved passive system, higher efficiency conversion device, improved service control and decreased service level. The results are broadly comparable within each occupancy pattern. Although savings with the full passive system improvements (wall and roof) are the highest for each occupancy pattern, they can also be most expensive, especially for solid wall houses. In finding that combinations of less expensive and less invasive measures can generate similar savings, the case for promoting these options is strengthened.

In recent years, policy initiatives have encouraged the uptake of high efficiency condensing boilers and insulation. These policy focuses have been demonstrated to be well assigned, with improved wall insulation and boiler efficiency showing the greatest saving potential out of the single measures and combined wall and roof insulation resulting in the greatest savings in all three occupancy patterns. Zonal heating controls exhibit significant savings, particularly for the working couple who have a more variable occupancy pattern and therefore benefit from a reduction in the time for which the house is heated whilst unoccupied. Further policy work for the promotion of zonal and other advanced heating controls is therefore to be encouraged. Partial heating reveals greatest savings for the couple present in the daytime as the unoccupied space is greater than for a family, and the time over which heating is reduced is longer. The effects of reducing the service level in terms of internal temperature present large variations determined by the extent of temperature reduction. If personal heating can be promoted to maintain the occupants’ thermal comfort, or societal expectations for internal temperatures can be relaxed, large savings can be attained for minimal cost and disruption.

The variations in energy consumption predicted by the model are not as large as have been measured between similar houses [51,62], and this could be explained by the observation that occupancy characteristics include more than the occupancy pattern discussed here. Other factors, such as opening windows and doors for ventilation, and use of secondary heating will also contribute to the variations in energy consumption for different occupants. The initial state of a building is another key factor in the size of, and variation in, calculated energy savings. In this study, for the sake of simplicity, the initial state of the house and its occupants was based on a 'typical' UK dwelling, but with a larger variation in initial state, a wider range of saving would expected. The savings calculated will also depend on the extent to which EEMs are implemented; the sensitivity of savings to some parameters has been illustrated to some extent in the consideration of three levels of improved insulation and two levels of temperature reduction. Internal demand temperature has been identified as the most significant parameter in sensitivity analyses published in other papers [63–65], followed by heating system efficiency, external temperature, total floor area, storey height and daily heating hours [65]. Further sensitivity analysis of the model used in this paper could allow more robust comparison of the scenarios investigated, including different starting points and levels of improvement. However the approach used in this paper has been to use common and realistic values for all modelling parameters to allow the comparison of different methods of energy efficient retrofit.

In reality, some EEMs are going to be more appropriate in some cases than others, and this must always be taken into account when making recommendations for the adoption of such measures. For example temperature reduction may not be suitable for those occupants who are elderly or suffering from health conditions, the use of advanced heating controls will not suit all types of people, insulation is not easily applied to all houses, and cost constraints will limit some households more than others. When applying this analysis to individual households and buildings, these further context specific details could take the application beyond the three occupancy patterns explored in this paper. Conversely, passive system and conversion device measures resulted in similar savings for all three occupancy types and therefore exhibited greatest resilience to changing households; this is in agreement with findings by De Meester et al. [17]. Thus these measures can be particularly recommended in houses with a high turnover, such as the rental sector. The improvement afforded by EEMs depends on the initial state of the building and this always needs to be taken into account in any savings calculations as opposed to the typical values which have been used as representative examples in this paper. The degree to which EEMs are implemented could be better represented in building modelling as a scale of savings attainable, rather than distinct values. The sensitivity of other aspects could then be included and an understanding of where different combinations of measures would place savings on the scale could provide information to decision makers.

## 6. Conclusions

The aim of this work has been to investigate the effectiveness of EEMs for different occupancy patterns, motivated by evidence that occupancy has a significant effect on domestic energy consumption. The study has enabled us to determine whether the current approaches to energy efficiency in homes are appropriate or if other types of EEMs should be more widely promoted.

It has been found that there are comparable savings predicted from different approaches to delivering heating thermal comfort with lower energy demand. Our results provide evidence that combinations of less expensive and less invasive energy efficiency measures can generate similar savings to passive systems (insulation) and conversion devices (boilers), and therefore the case for promoting these options is strengthened. The savings have been shown to vary depending on the occupancy pattern of the household, and consequently building assessments and savings estimates should be context specific.

Overall, this paper has contributed to the understanding of how occupancy patterns affect domestic energy consumption and energy savings for a broad range of EEMs, and this can inform policy as well as individual decisions made to reduce the energy consumption of the housing sector.

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